Overcoming Dynamic Disturbances in Imaging Systems

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ABSTRACT

We develop and discuss a methodology with the potential to yield a significant reduction in complexity, cost, and risk of space-borne optical systems in the presence of dynamic disturbances. More robust systems almost certainly will be a result as well.

Many future space-based and ground-based optical systems will employ optical control systems to enhance imaging performance. The goal of the optical control subsystem is to determine the wavefront aberrations and remove them. Ideally reducing an aberrated image of the object under investigation to a sufficiently clear (usually diffraction-limited) image. Control will likely be distributed over several elements. These elements may include telescope primary segments, telescope secondary, telescope tertiary, deformable mirror(s), fine steering mirror(s), etc. The last two elements, in particular, may have to provide dynamic control. These control subsystems may become elaborate indeed. But robust system performance will require evaluation of the image quality over a substantial range and in a dynamic environment. Candidate systems for improvement in the Earth Sciences Enterprise could include next generation Landsat systems or atmospheric sensors for dynamic imaging of individual, severe storms. The technology developed here could have a substantial impact on the development of new systems in the Space Science Enterprise; such as the Next Generation Space Telescope(NGST) and its follow-on the Next NGST. Large Interferometric Systems of non-zero field, such as Planet Finder and Submillimeter Probe of the Evolution of Cosmic Structure, could benefit. These systems most likely will contain large, flexible optomechanical structures subject to dynamic disturbance. Furthermore, large systems for high resolution imaging of planets or the sun from space may also benefit. Tactical and Strategic Defense systems will need to image very small targets as well and could benefit from the technology developed here.

We discuss a novel speckle imaging technique with the potential to separate dynamic aberrations from static aberrations. Post-processing of a set of image data, using an algorithm based on this technique, should work for all but the lowest light levels and highest frequency dynamic environments. This technique may serve to reduce the complexity of the control system and provide for robust, fault-tolerant, reduced risk operation. For a given object, a short exposure image is "frozen" on the focal plane in the presence of the environmental disturbance (turbulence, jitter, etc.). A key factor is that this imaging data exhibits frame-to-frame linear shift invariance. Therefore, although the Point Spread Function is varying from frame to frame, the source is fixed; and each short exposure contains object spectrum data out to the diffraction limit of the imaging system. This novel speckle imaging technique uses the Knox-Thompson method. The magnitude of the complex object spectrum is straightforward to determine by well-established approaches. The phase of the complex object spectrum is decomposed into two parts. One is a single-valued function determined by the divergence of the optical phase gradient. The other is a multi-valued function determined by the circulation of the optical phase gradient-"hidden phase." Finite difference equations are developed for the phase. The novelty of this approach is captured in the inclusion of this "hidden phase." This technique allows the diffraction-limited reconstruction of the object from the ensemble of short exposure frames while simultaneously estimating the phase as a function of time from a set of exposures.

The following subsections of the paper are included: Introduction, Technical Approach, Plans, Preliminary Results of earlier work and a Conclusion.

1. Introduction

The desired result of this new algorithm is the development and verification in a laboratory setting of a technique to reduce the sensitivity and improve performance of NASA and DOD optical systems in dynamic environments. On the ground and in the laboratory such systems are sensitive to and the performance is degraded by atmospheric turbulence, laboratory seeing, and motion/jitter of key optical elements. In space the sensitivity of such optical systems is primarily to jitter; however some effects of downward looking through an atmosphere may still be presence. Of course, seeing effects may still be present if the system is sealed and operating at non-zero pressure. In any event the development envisioned here will be able to improve algorithms that compute system performance. A key feature of the improvement lies in the inclusion of the "hidden phase" component in this algorithm.

We intend to investigate the improvement, our technique offers, in the context of various system architectures. For large, space systems with flexible structures various control architectures will be applied. Control will most likely be distributed over several elements. These elements can include primary mirror segments, secondary, tertiary, deformable mirror(s)-DM(s), Fast Steering Mirror(s)-FSM(s), etc. The control subsystem goal is to improve a system with substantially aberrated imaging to diffraction-limited imaging. Further the control subsystem will have to ameliorate the effects of temporally and spatially varying disturbances. It is in the realm of the temporally varying disturbances that this algorithm will be most effective. Indeed it is the hope that it can eliminate the need for any higher order aberration correction in the temporal domain and leave perhaps just a simple two-axis FSM. Post-processing using this algorithm will work at all but the lowest light levels. Realistic estimates of light-level limits on performance will be investigated.

Space systems of the future will be driven to lighter weight and lower areal densities for the optics. Such systems tend to be flexible and therefore prone to dynamic/jitter effects. For all NASA and DOD systems, sources of dynamical disturbances/jitter are certainly reaction wheels (as well as other stabilization devices), detector coolers, as well as other sources.

The Severe Storm type of mission may be particularly exciting and challenging, since the object of study (a single storm cell) is time evolving. The nature of the temporal disturbances onboard the satellite and those in the object will have to be studied and separated. Other geostationary systems may also benefit, such fourier transform spectrometers and other advanced meteorological satellites. Low earth orbiting systems such as Landsat may benefit as well.

The technology developed here could have a substantial impact on the development of new space telescopes; such as the Next Generation Space Telescope(NGST) and its follow-on the Next NGST. Large Interferometric Systems of non-zero field, such as Planet Finder and Submillimeter Probe of the Evolution of Cosmic Structure, could benefit. These systems most likely will contain large, flexible optomechanical structures subject to dynamic disturbance. Furthermore, large systems for high resolution imaging of planets and the sun would like benefit from this technology.

Positive results from this approach could lead directly to a high accuracy (near diffraction-limited) system for imaging in the presence of various disturbances, including vibration. Further, our approach has the potential to reduce cost and risk for large, light-weight systems in many potential applications. This approach is innovative and requires development to enhance its technology readiness. But it is believed to hold great promise for improvements.

For high power level systems, mainly DOD tactical and strategic systems, coolant flow induced jitter may be a significant source of disturbance. We have enumerated some specific types of systems that may be candidates for improvement.

Flowing from this development may be significant reduction in the complexity of space-borne optical systems. Consequent significant reductions in cost may also accrue form such a reduction in complexity. More robust systems may be a result as well. The output from this development quite likely would be a quantitative and qualitative reduction in risk for such space missions.

2. Technical Approach

This section of the proposal is divided into three sections. In the first section we present an overview of the speckle imaging technique to be used in this investigation. Secondly we elaborate the specifics of the Knox-Thompson approach used here and explain the enhanced feature; the development of the hidden phase. In the last section we discuss the particular plan to be followed in the future.

2.1 Overview

Speckle imaging techniques have been evolving since the fundamental idea was presented almost 30 years ago.[1] Labeyrie's key observation was that the speckles in short exposure images contain richer spatial frequency information than long exposures. The speckle imaging technique can be described as follows.[2] Two data sets are required to perform this imaging; one set of RO short exposures images of the object under study and one set RR of similar images of a bright, nearby reference. Normally, values of RO and RR are on the order of tens or hundreds, driven by signal-to-noise ratio considerations. Exposure times are typically a few to tens of milliseconds.

The first step in the process is to compute the fourier transform of the images. Next one computes the modulus squared and the cross spectrum or bispectrum. We use the cross spectrum obtained by the Knox-Thompson method. Statistics are then accumulated and the process is repeated either RO or RR times as appropriate. Then one computes the average modulus squared and the average cross spectrum or bispectrum. Continuing, one deconvolves the image modulus squared and computes the phase spectrum. Finally the fourier modulus and phase data are combined; the inverse transform is computed; and the image estimate is obtained.

Many methods exist to find the modulus and we will not elaborate them here. We will explain our approach below. Iterative methods start with the modulus and proceed along the following lines. First the inverse FFT is computed. Next the constraints are imposed. Finally the FFT is computed to obtain the phase and the process is iterated. We use a method to directly compute the phase using difference equations.

2.2 Detailed Approach

Here, we will concentrate on the particular implementation called the Knox-Thompson, or cross-spectrum, method and, in particular, deal with the object spectrum phase reconstruction.[3]

We label the arrays of short-exposure data as:

$$d(l;i,j). \qquad (1)$$

The index l = 1,2, … R labels the frame, while the next two indices, (i,j), label the pixel in the array. We take a two-dimensional Finite-Fourier-Transform (FFT) on the pixel indices as:

$$\tilde{d}(l;m,n) = FFT\{d(l;i,j)\}. \tag{2}$$

The array indices, m and n, label the elements of the two-dimensional FFT. The zero spatial frequency point is labeled $(\bar{m}, \bar{n})$. We then form the unbiased cross-spectra as [4]

$$C_x(m,n) = \frac{1}{R}\sum_{l=1}^{R} \left\{\tilde{d}(l;m,n)\,\tilde{d}^*(l;m+1,n) - \tilde{d}^*(l;\bar{m}+1,\bar{n})\right\}$$

(3)

$$C_y(m,n) = \frac{1}{R}\sum_{l=1}^{R} \left\{\tilde{d}(l;m,n)\,\tilde{d}^*(l;m,n+1) - \tilde{d}^*(l;\bar{m},\bar{n}+1)\right\}.$$

in which we have picked one unit offset in each direction in the FFT; other offsets can easily be analyzed, however, the unit offset choice gives the best accuracy on the high-spatial-frequency phase. The ensemble averaging over many realizations of the turbulence-induced phase screens makes the cross-spectrum transfer functions real-valued. [3] Therefore, the turbulence-induced phase errors are averaged away and the phase of the cross-spectrum can be directly related to phase differences in the object spectrum.[4] The remaining phases of these two cross-spectra lead to two two-dimensional difference equations for the phase of the object spectrum as:

$$C_x(m,n) = |C_x(m,n)| \exp(i\,V_x)$$

(4a)

$$C_y(m,n) = |C_y(m,n)| \exp(i\,V_y),$$

in which the cross-spectrum phases, V_x, V_y, are related to the object spectrum phase, W, as:

$$V_x(m,n) \equiv W(m,n) - W(m+1,n)$$

(4b)

$$V_y(m,n) \equiv W(m,n) - W(m,n+1).$$

In a new paper[4] these equations for the object spectrum phase are solved[4]; we will refer to these equations as "phase flow" equations. In the derivation[4] we first define discrete gradient, divergence and curl operations, followed by our proof that the phase flow on the FFT-grid can be decomposed into an irrotational part with zero curl and a rotational part with zero divergence. Next in the derivation[4] we will demonstrate that in a similar fashion, the object spectrum phase can be decomposed into a regular single-valued function determined by the divergence of the phase gradient, as well as a multi-valued function determined by the circulation of the phase gradient; this second function has been called the "hidden phase".[5] We will present a solution method that gives both the regular and hidden parts of the object spectrum phase. Elsewhere it is also demonstrated[5] that the standard least-squares solution to the two-dimensional difference equations will only generate the regular part of the phase, while always missing the hidden part. In the preliminary results section , we will give several examples of imaging through turbulence and post-processing, augmenting the Knox-Thompson method with a hidden phase algorithm. In particular, we will compare reconstructions with and without the hidden phase component included in the reconstruction algorithm. Finally, in the conclusion we discuss prospects for the method, as well as ongoing problem areas.

The solution difficulties associated with the cross-spectrum phases are reasonably well-known. In 1986, Fontanella, et. al. provided a discussion of the effects of phase dislocations on the phase reconstruction.[6] In 1987, Takajo, et. al. acknowledged the difficulty of phase reconstruction near isolated zeroes in the object spectrum and proposed a solution.[7] More recently, several authors have presented branch-point tolerant phase reconstructors.[8,9,10] The present paper[4] adds to these results by emphasizing a unique decomposition of the phase flow into an irrotational and a rotational part. We feel that this approach lends considerable clarity to the phase reconstruction problem. Furthermore, we specifically treat phase reconstruction in the Knox-Thompson speckle imaging method, providing a post-processing algorithm that appears to be very effective for ground-based astronomy applications.

We have mentioned above that we can decompose the vector phase flow into a piece with zero divergence, and a piece with zero circulation . That a continuous vector field can be decomposed into rotational and irrotational parts has proved quite useful in hydrodynamics for nearly 150 years.[11] Our results are a discrete analog of those well-known results.

2.3 Plans

We now present the future direction for conducting this development. It can be decomposed into four phases. These phases are enumerated below:

(1) Complete application of the method to the atmospheric turbulence case
(2) Develop disturbance model for the space environment
(3) Obtain calculated results for this environment
(4) Develop designs and plans for laboratory demonstrations of the technique.

The first phase will entail expanding on results already obtained for atmospheric compensation and to be briefly described below. This work will include assessing precision of the method and developing light level/dynamic range models. Other source objects including distributed ones will be investigated. The modeling of laboratory (horizontal) seeing effects will commence

The second phase will cover the development of the jitter model for two candidate prototype systems; one a two element telescope system and the other a large observatory with three or four main telescope elements. Jitter sources on spaceborne systems will be investigated such as gyros, stabilization subsystems, cryogenic subsystems, cooling subsystems, etc. Disturbance sensitivities of the optical subsystem will be explored, such as motion of key optical elements (secondary, tertiary, etc.) and the detector. The impact of the statistical distribution functions (Gaussian, Poisson, etc.) will be incorporated. Lab seeing effects will be fully incorporated. Development of typical system transfer models will start. In these models we will determine the attenuation of the disturbances expected with candidate control systems and the resulting residual after control.

In the third phase we will fully exercise the baseline algorithm on typical source objects with known jitter disturbances present. Image reconstruction performance of the algorithm will be thoroughly evaluated. Again we will assess precision of the method and develop light level/dynamic range models. Other source objects including distributed ones will be investigated as before for atmospheric compensation. System transfer performance will be fully evaluated for the two specific candidate systems mentioned in the paragraph above. Comparison of this speckle-imaging algorithm to other such approaches will be started. The relationship of speckle approaches to phase retrieval and phase diversity reconstruction approaches will be addressed.

In the final phase, a laboratory demonstration concept will be developed. A simple, probably two element, telescope system will be designed and analyzed. A surrogate source will be imaged on a CCD detector. Stingers will be identified for the telescope secondary and the detector to introduce jitter.

The performance of the image reconstruction process in the presence of known disturbances and Known sensitivities will be analyzed .The comparison of this speckle imaging algorithm to other such approaches will be finished. The relationship of speckle approaches to phase retrieval and phase diversity reconstruction approaches will be further addressed. Avenues to obtain actual hardware and lab space will be pursued.

3. Preliminary Results

In this section, we will demonstrate image reconstructions, using the Knox-Thompson Method augmented by our complete solution for both the regular and hidden parts of object spectrum phase. Figure (1a) plots a diffraction-limited image of a four-star group, in which one of the stars is twice the intensity of the other three. (We show all figures on a gray scale on which the original 32 x 32 intensity data is bilinearly interpolated to a 256 x 256 grid. The specific bilinear interpolation method is in Ref. 12.) Figure (1b) shows a turbulence-degraded, long-time exposure of the identical asterism. Here, we have averaged 640 short exposures, using aberrated point-spread functions. In addition, we have added shot noise to each pixel (32 x 32 array) in each short-exposure frame, while assuming 10,000 photons per frame.

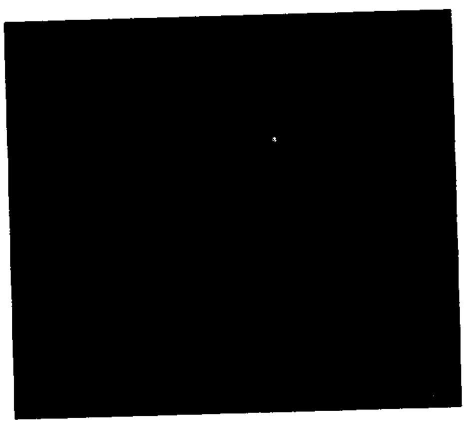

Figure 1a.) Diffraction-limited

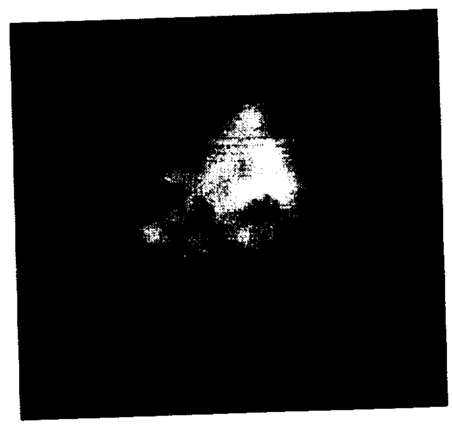

Figure 1b.) Long-time average with $D/r_0 = 10$.

We use standard speckle methods, as described in reference 1, to determine the modulus of the object FFT. In this step, we use an independent set of reference star short exposures, in order to deconvolve the speckle transfer function from the modulus of the object FFT. We then use the Knox-Thompson method to generate difference equations for the phase, and to solve for both the regular, W^S, and multi-valued, W^H, components of the object FFT phase.

Prior to taking the inverse FFT, we multiply by the optical transfer function, $H_{DL}(m,n)$, of the diffraction-limited telescope. The final diffraction-limited object reconstruction is then given as

$$I(i,j) = FFT^{-1}\left\{ \left|\tilde{I}(m,n)\right| \; e^{i\left(W^S(m,n) + W^H(m,n)\right)} \; H_{DL}(m,n) \right\}.$$

This reconstruction is plotted in Fig. (1c); the reconstruction accuracy is excellent. If we affect the identical reconstruction procedure, but use a minimum least-squares phase estimator, then the hidden phase is not included in the object FFT estimate. The reconstruction results with the hidden phase neglected are shown in Fig. (1d). Obviously, the hidden phase plays a critical role in the reconstruction process.

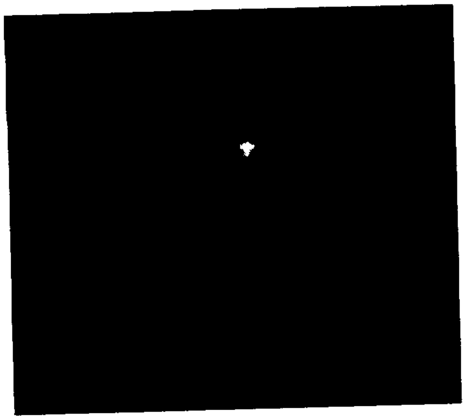

Figure 1c.) Reconstruction with hidden phase.

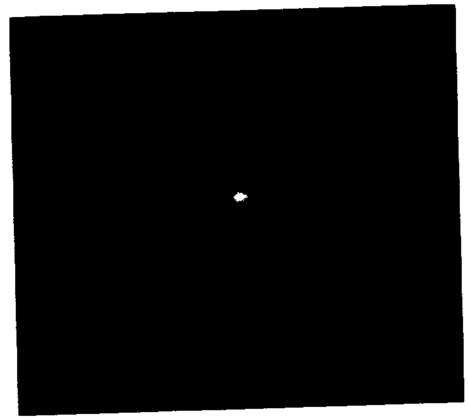

Figure 1d.) Reconstruction without hidden phase.

As a second example, Fig. (2a) shows a contour plot of a diffraction-limited image of a binary star in which one star is twice the intensity of the other. Figure (2b) shows the turbulence-degraded , long-time average of 640 short exposures with 10,000 photons per frame. Using the augmented Knox-Thompson procedure, we obtain the results in Fig. (2c) In this simpler object case, there are no zeroes in the original object spectrum, and the hidden phase is essentially zero. Figure (2d) shows the reconstruction when the hidden phase is set exactly to zero. The results are excellent in either case.

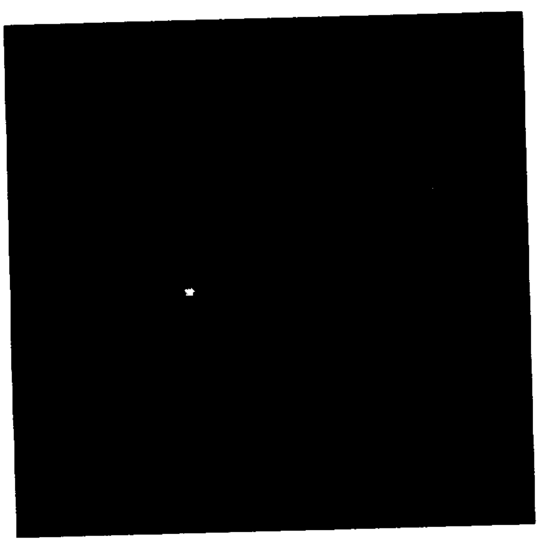

Figure 2a.) Diffraction-limited binary image.

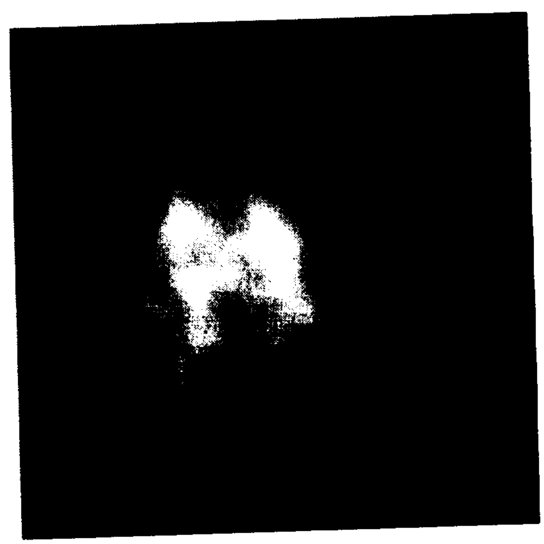

Figure 2b.) Long-time average with $D/r_0 = 10$.

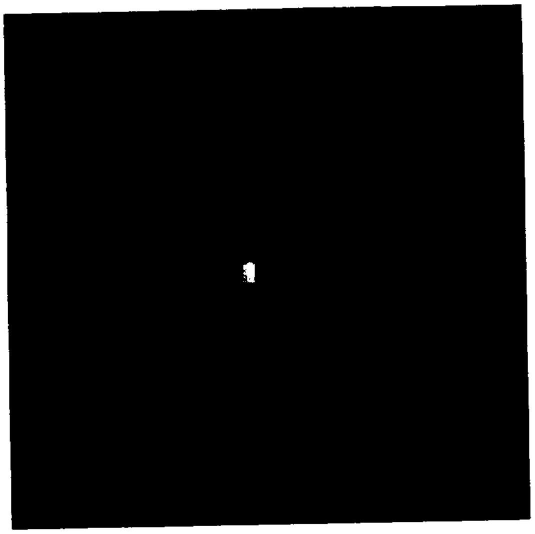

Figure 2c.) Reconstruction with hidden phase.

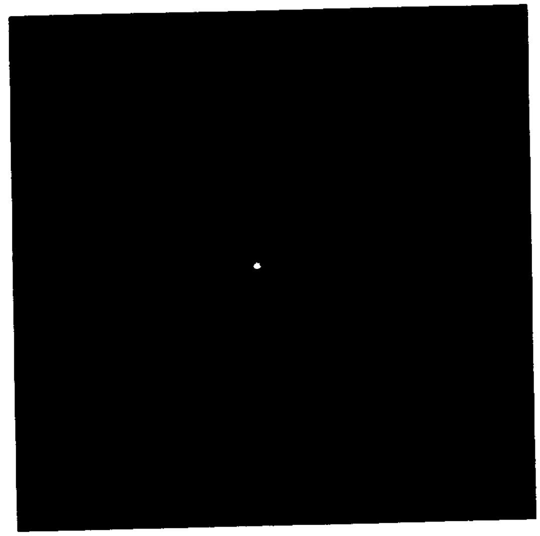

Figure 2d.) Reconstruction without hidden phase.

4. Conclusion

The Knox-Thompson, or cross-spectrum, method provides two two-dimensional difference equations for the phase of the object spectrum. A complete solution to these difference equations can be decomposed into a regular single-valued function, W^S, determined by the divergence of the phase gradient, as well as a multi-valued function, W^H, determined by the circulation of the phase gradient. Furthermore, this phase decomposition is unique and complete. An accurate object spectrum reconstruction then requires a modulus estimate, as well as both parts of the phase. For almost any object on the celestial sphere more complicated than an unequal magnitude binary, both components of the object spectrum phase are needed for an accurate reconstruction. Knox-Thompson reconstructions based on a minimum-least-squares phase estimator will usually be of limited value.

The examples in Section 3 demonstrated reconstructions on 640 short-exposure frames in the presence of significant turbulence and shot noise. In addition, we have tested the method with realistic shot and read noise corrupting the short-exposure data. Although our augmented Knox-Thompson method worked well in these examples, as well as in many other test problems, several questions remain: Is the method an optimum method in the presence of noise? Is there a better way to motivate or derive our method for filtering the phase flow circulation values? Can we quantify the reconstruction accuracy as a function of turbulence strength, photons per frame, and number of data frames? These questions, along with other evolving issues, will require further investigation.

The technology developed here could have a substantial impact on the development of new space telescopes; such as the Next Generation Space Telescope(NGST) and its follow-on the Next NGST. Large Interferometric Systems of non-zero field, such as Planet Finder and Submillimeter Probe of the Evolution of Cosmic Structure, could benefit. These systems most likely will contain large, flexible optomechanical structures subject to dynamic disturbance. Furthermore, large systems for high resolution imaging of planets or Earth from space may also benefit. Such systems could include next generation Landsat systems or atmospheric sensors for dynamic imaging of individual, severe storms. Tactical and Strategic Defense systems will need to image very small targets as well and could benefit from the technology developed here.

We believe our technique offers improvement in the context of various system architectures. For large, space systems with flexible structures various control architectures will be applied. Control will most likely be distributed. The control subsystem goal is to improve a system with substantially aberrated imaging to diffraction-limited imaging. In the realm of the temporally varying disturbances our algorithm is expected to be the most effective. Indeed it is the hope that it can eliminate the need for any higher order aberration correction in the temporal domain and leave perhaps just a simple two-axis FSM. Post-processing using this algorithm will work at all but the lowest light levels. Realistic estimates of light-level limits on performance will be investigated. This algorithm could in the future be applied and the software written for a specific flight project.

This investigation may yield significant reduction in complexity, cost, and risk (quantitative and qualitative) of space-borne optical systems by overcoming dynamic disturbances. More robust systems almost certainly will be a result as well.

5. Acknowledgement

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6. References

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